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Analysis of interfacial debonding of geopolymer annular sealing in CO_2 geo-sequestration wellbore

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Abstract

For the geological sequestration of atmospheric CO_2 to be viable, it is important that leakage of stored gas back to the atmosphere is prevented for a long period. Apart from other modes of failure, damage of the bond between interfaces can open up migratory pathways for leakages of CO_2 to occur. A stress induced debonding mechanism for well bore interfaces has been studied. A numerical modelling approach was used to investigate a wellbore composite cylinder system using finite element software. Analysis was performed for the wellbore annular cement sheath, both for static pressure and temperature increase/decrease. In addition, geopolymer, a novel acid resistant cementitious binder, has been considered as an annular cement system. From analysis, it has been observed that debonding can occur at discrete locations for the wellbore pressure and/ temperature increase. However, for the wellbore pressure and/ temperature decrease, it was found that stress-slip failure occurs when tensile normal stresses along interfaces equal the interfacial bond strength. In addition to that, for pressure and/ temperature decrease, shear stresses developed in the circumferential direction appeared insignificant in debonding failure. Thermal dilation of wellbore material can help preventing discrete debonding of wellbore interfaces in the case of wellbore pressure and temperature increase. Conversely, a wellbore temperature decrease contributes to microannular formation along interface because of the material shrinkage effect.

Keywords: Geo-sequestration; geopolymer; debonding; crack initiation; stress-slip failure;

1. Introduction

To ensure safe and effective storage of CO_2 in geological reservoir it is important that long term leakage of stored gas is prevented. In between reservoir and the atmosphere there are several potential pathways for leakages to occur. The most vulnerable leakage pathways are the debonded interfaces between well bore cylinders i.e. between casing and cement or cement and formation. Once debonded ,

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both the interfaces can open up with time and establish a migratory channel for escape of CO_2 back to the atmosphere.

Interface bond can be destroyed in two different ways; shear bond failure and hydraulic bond failure. The first failure type relates to the mechanical debonding due to stresses induced along interfaces. On the other hand, hydraulic bond failure accompanies the decoupling and widening of microannulus of two contacts faces (either casing and cement or cement and rock) under the action of fluid pressure. It is important to note here that occurrence of one type of bonding failure does not necessarily coincide with the other. Recent study on wellbore interfacial debonding by Brice et al. [1] put emphasis on hydraulic pressure induced debonding. However past studies on geomechanical failure analysis of wellbore sealant described to some extent the mechanism of debonding failure by mechanical stresses. Study made by Bosma et al. [2] concluded that debonding processes are dependent on relative stiffness between the sealant and the rock and also on the presence of anisotropy. Study by Barlet-Gouedard et al. [3] identified the formation of microannulus in case of Portland based oil well cement. However, many aspects of interface debonding failure are still unknown and further study is required.

Either drilled initially for petroleum/oil production or mere geo-sequestration purpose, wellbore construction or operation processes are accompanied by huge fluctuation in temperature and pressure profile. These variations can be any combination of wellbore over-pressurization or depressurization with thermal heating or cooling. Thereafter, high pressure and high temperature loading induces complex stress states ranging from highly tensile to compressive. Stresses so induced can initiate cement defects like debonding crack. These defects or cracks form the potential locations where hydraulic pressure can act to instigate further propagation of cracks and thereby can establish a full vertical migratory channel. Therefore, though hydraulic debonding has been identified as dominant cause of bond failure in wellbore hydrodynamic environment, study and analysis of causes of mechanical debonding still bears importance. In fact, stress induced debonding not only create microannulus or leakage path but also create discontinuities for hydraulic action to promote debonding further. Thus, by lowering the interface mechanical defects, risk of leakage by debonding failure can be minimized.

Instead of conventional cement system, this study considered geopolymer as annular cement system. Geopolymer is an alkali-activated, acid-resistant inorganic polymeric material. Because of its material attributes such as acid-resitivity, low permeability and high temperature favoured curing regime, geopolymer has already been recognised as a potential sustainable cementitious material.

The present study focuses on the debonding mechanism of wellbore interfaces for the application of different pressure and temperature loading scenarios. A numerical modelling approach is used to investigate wellbore composite cylinder system using finite element software. Material data for geopolymer are gathered from experimental results. However, model input for casing steel and formation rock is collected from literature. Analysis is performed both for pressure and temperature increase or decrease. Interface elements are used at contacts (casing-cement and cement-formation) to simulate nonlinear bond failure at interface.

2. Model Description

Model is built on 2D space considering idealized plain strain condition. In other words, pseudo 3D condition is simulated taking a wellbore 2D cross-section perpendicular to the vertical axis. Cylinder interfaces are modeled as bonded by using 2D interface elements. Considering rotational symmetry, a quarter of wellbore geometry is chosen for analysis. Two support faces are found exposed along wellbore radius having aligned with x and y co-ordinate directions. For support face along x-direction, y-displacement is kept zero and x-displacement is free. On the other hand, for support face along y-direction, x-displacement is zero and y-displacement is free. Semi-infinite boundary elasticity is simulated at outer surface of formation rock by using spring support at outer periphery.

ATENA Engineering 2D, a commercial finite element computer software extensively used for nonlinear analysis of brittle material (such as concrete, rock etc.) is used to run the model. The constitutive model comprises the use of Rankine failure criterion for tensile (fracture) behavior and Menetrey-William failure surface for compressive behavior. In order to eliminate the computational error in simulation results due element size effect, instead of conventional smeared crack approach, ATENA model uses Bazant's smeared crack (banded smeared crack) model to simulate crack in brittle material.

2.1 Geometry and material properties

Wellbore geometry has been chosen in light of Well R-3H in Kristing oil field of Norway [4] and dimensions are provided in Table1. Material model used for casing steel is 'Plain Strain Elastic Isotropic' in ATENA 2D. On the other hand, material model '3D (plain strain idealization) Non Linear Cementitious2' as provided in ATENA Engineering 2D is used for cement and rock. Input data for material model for casing steel and formation rock are collected from the literature. However, input data for geopolymer cement are gathered from two sources. Mechanical parameters such as strength, elastic modulus, Poisson ratio etc. are obtained directly from the experimental stress-strain relationship for the material tested in triaxial stress-state condition by us. However, geopolymer tensile strength and fracture energy values are used from [5]. Data for all materials are compiled and presented in Table2.

Table1: Wellbore Model Geometry

Wellbore Component	Internal Radius (mm)	External Radius (mm)
Casing cylinder	108.40	122.25
Cement Sheath cylinder	122.25	155.58
Formation cylinder	155.58	254.00

'2D Interface' material model is used for casing-cement and cement-formation interfaces. Same values of material properties are used for both interfaces. Values for interface tensile strength, cohesion and friction factor are used respectively as 5 MPa, 2 MPa and 0.3. Interface stiffness is assumed as 10 times of cement stiffness.

Table 2: Input Data for Wellbore Materials

Casing / Cement / Formation Type	Young's Modulus (GPa)	Poisson Ratio	Ultimate tensile strength (MPa)	Ultimate Compressive strength (MPa)	Fracture Energy (MN/m)	Coefficient of Thermal Expansion (/K)
P110 grade Casing	200.0	0.27	-	-	-	0.000013
Geopolymer	12.8	0.20	3.3	80	0.0091	0.00000955
Shale	10.0	0.30	2.0	60	0.0091	0.000012

2.2 Wellbore loading

Other than gravity (self) load, a typical wellbore experience loads from changes in pressure and temperature. Wellbore processes which potentially cause pressure and temperature variation in a cased wellbore section are drilling of the wellbore, the stimulation and production of the reservoir, integrity and leak off test, perforation of casing etc. On the other hand, there is external static pressure due to overburden or lithospheric pressure or far field stresses.

Study by Mainguy et al. [6] stated pressure decrease of 25 MPa during production with a subsequent increase of 15.5 MPa during abandonment. They also mentioned significant pressure drop of 20 MPa and 12 MPa for the surrounding cap rock layers in contact with the reservoir and away from the reservoir respectively. Similar study on wellbore pressure and temperature changes with CO_2 injection operation for an injector wellbore was performed by Erik [7]. As outlined by [7], the pressure and temperature profiles along the well vary with the phase composition of CO_2. The study showed that when the gas volume fraction is zero at the well head, maximum bottom pressure of 16 MPa occurs with a corresponding temperature of 313 K.

Based on the literature stated in above paragraph, the present study considered following wellbore pressure and temperature loading:

Loading 1: Well internal pressure increase of 16 MPa;

Loading 2: Well pressure decrease of 25 MPa;

Loading 3: Well temperature increase of 313 K and pressure increase of 16 MPa;

Loading 4: Well pressure decrease of 25 MPa and temperature decrease of 313 K;

Both loading 3 and loading 4 are simulated for two different values of rock thermal expansion coefficient. Loading 3 with rock thermal expansion coefficient of 0.000016 /K and 0.000012 /K are designated respectively as pressure and temperature increase 1 and pressure and temperature increase 2. On the other hand, loading 4 with rock thermal expansion coefficient of 0.000016 /K and 0.000012 /K are designated respectively as pressure and temperature decrease 1 and pressure and temperature decrease 2.

3. Results and Discussion

3.1 Mesh sensitivity

One drawback of modeling with finite element software is that its results are greatly influenced by the size of finite element or mesh density. In practice, finer mesh is adopted to overcome this dependency. For a particular geometry there is always a required density of mesh at which the model is stable.

We meshed our geometry into 3 different densities which yielded model with total element number of 130, 1890 and 2400. All three models were run for same material and loading input. Stresses and strains are plotted for a particular point in the cement sheath for the three different meshing. The results (Figure 1) show that stresses and strains obtained for total finite elements 1890 and 2400 are identical and almost follow the same line. However, model with total finite element 130 shows different stress-strain behaviour for the same observation point in the material. Therefore, for rest of the analysis performed in this study, we adopted the model with 1890 elements.

3.2 Crack initiations

Initiation and propagation of radial cracks from interface boundary is the most common happening in wellbore. Formation and propagation of these cracks are controlled largely by the material tensile strength. From the present study we find that initial crack density is function of interface material toughness. Interface toughness can be defined as the energy required for unit opening of the interface and can be found as the area under the stress- strain curve of interface material.

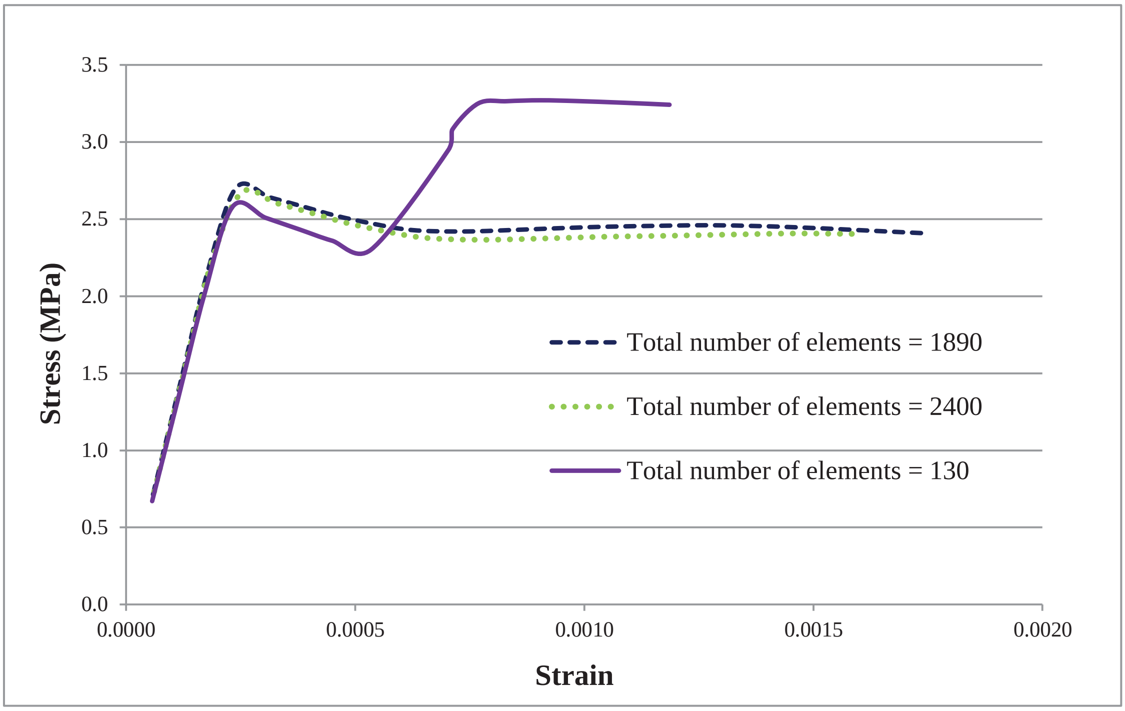

Figure 1. Stress-strain relationship at a material point near casing-cement interface for different mesh refinement for loading1

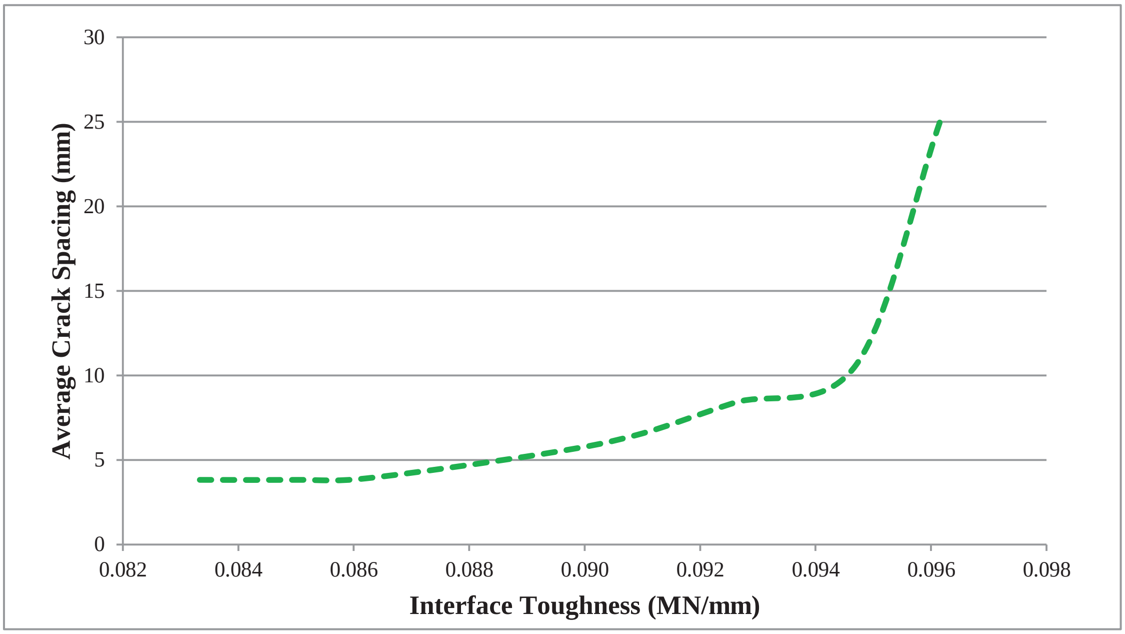

Figure 2. Change in crack spacing with interface toughness at crack initiation

Figure 2 depicts the variation of initial number of cracks with interface toughness. Lower the toughness, higher is the total number of cracks initiated. In other words, for a particular loading, crack initiation can be minimized by providing interfaces with sufficient toughness. Interface toughness relates to two key material parameters of the interface, namely, tensile stiffness and the tensile bond strength to the interface. Besides, radial crack initiation in the material indicates commencement of debonding, as well. Therefore, interface toughness appears to be an important property of material interfaces which control the initiation of debonding.

3.3 Interfacial debonding for pressure and temperature increase

It has already been demonstrated that [8, 9] when wellbore internal pressure and temperature increases, tangential stresses are tensile and radial stresses are compressive. Tensile tangential stresses can initiate cracks in the radial direction. However, formation of a debonding crack in the circumferential direction at interfaces seems unlikely for this type of wellbore loading and was not discussed in past studies [8, 9]. In the present study, it is observed that interface debonding and formation of subsequent microannulus can occur at discrete locations along interfaces for wellbore internal pressure and temperature increase. In fact, it is observed that these discrete discontinuities are located at points of confluence of radial cracks with interface line.

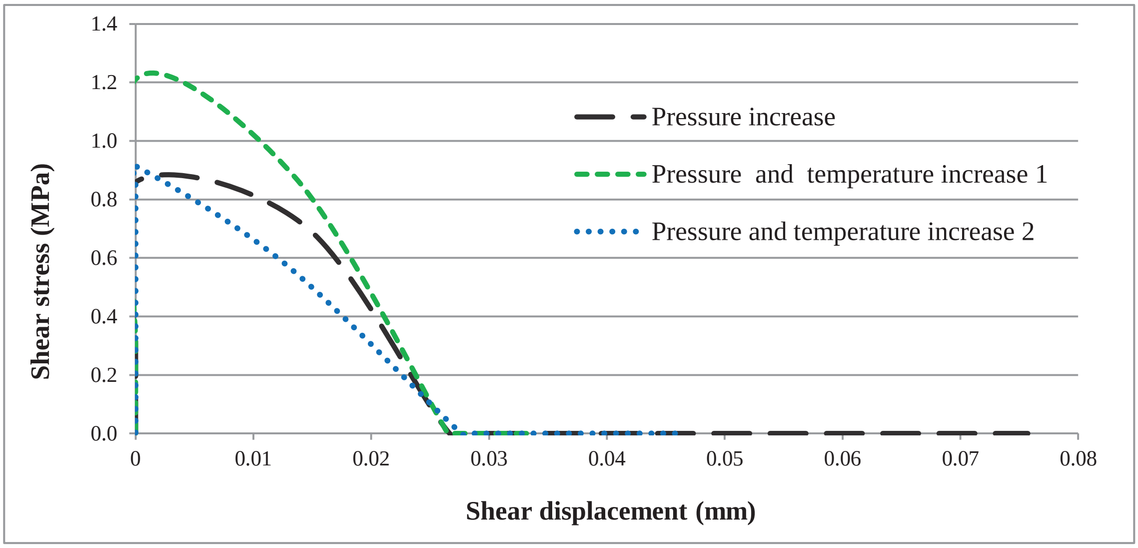

Figure 3. Shear stress softening at cement-formation interface due to wellbore pressure and temperature increase

Figure 5 and 6 illustrate location and nature of interface dislocation along cement-formation interface for wellbore internal pressure and temperature increase. Besides, Figure 3 shows the loss of interface shear stress with displacement. Plastic deformation occurs along interface circumference and causes plastic shear failure. As a consequence, shear crack is observed. From the plot (Figure 3), it can be noted that at failure, the maximum width of shear opening (along circumferential direction) is about 75 micron. On the other hand, maximum opening width (microannulus) in the normal direction is found as 46 micron (Figure 4). This value crosses threshold value of 10µm, the acceptable microannulus size already outlined [3].

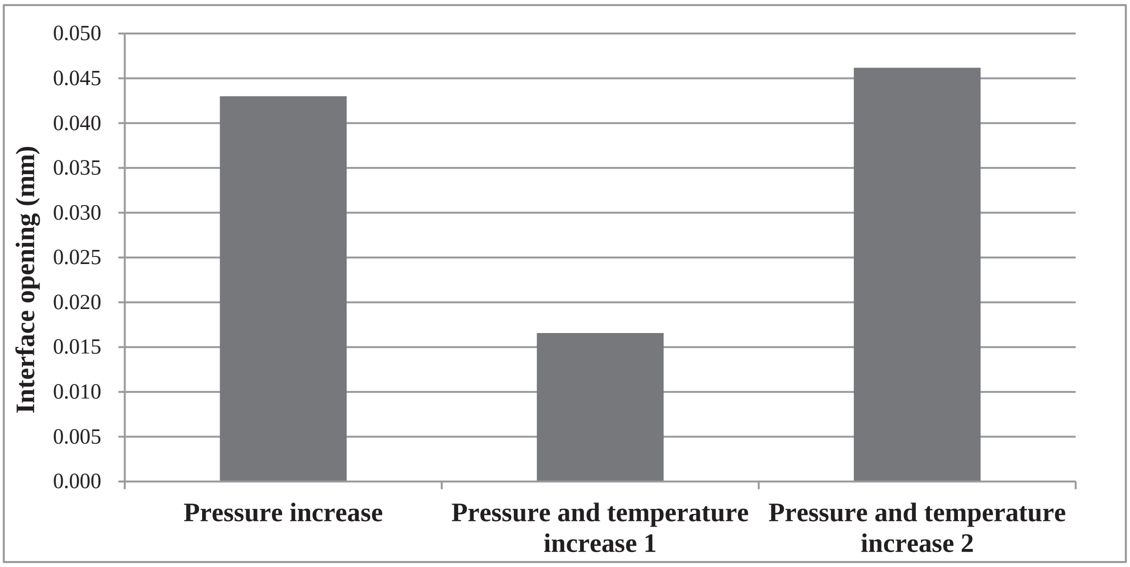

Figure 4. Maximum interface opening in normal direction at cement-formation interface due to wellbore pressure and temperature increase

In Figure 3, the plot for pressure and temperature increase 1 corresponds to increase of wellbore internal pressure to 16 MPa and temperature to 313 K (loading 3) with thermal expansion coefficient for formation rock as 0.000016 /K. On the other hand, the curve (Figure 3) for pressure and temperature increase 2 represents the same loading except coefficient of thermal expansion for formation rock being 0.000012 /K. It can be noted from the results that out of three scenarios, pressure and temperature increase 1 appears to be less damaging to the interface. Delayed failure and smaller microannulus width is observed for this scenario. Therefore, temperature increase with higher value of thermal expansion coefficient of formation rock appears least damaging because higher thermal expansion in the formation rock provide additional confinement to the interface and compensated for the normal displacement occurred at cement-formation interface.

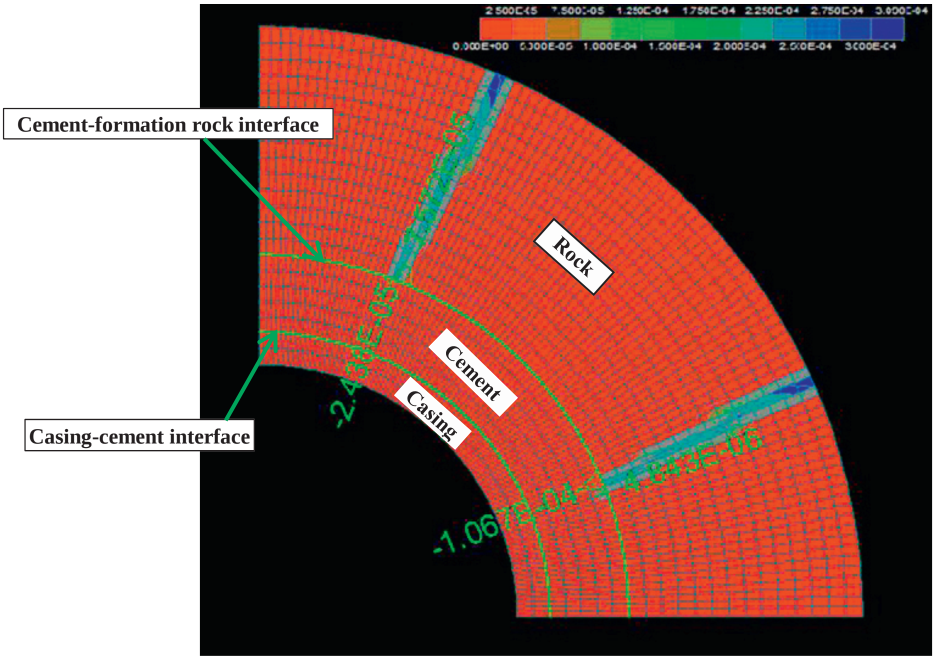

Figure 5. Radial crack formation and plastic shear displacement at cement-formation interface due to wellbore pressure increase

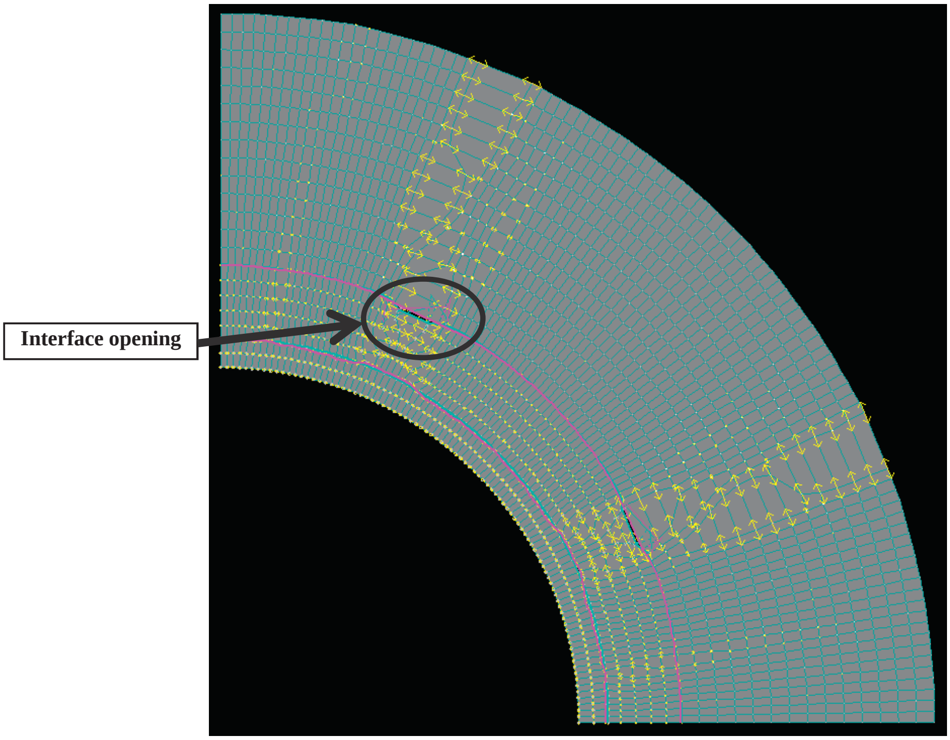

Figure 6. Principal strain direction and discrete debonding at interfaces due to wellbore pressure and temperature increase

3.4 Interfacial debonding for pressure and temperature decrease

Tensile radial stresses caused by wellbore pressure and temperature decrease has been identified as [8, 9] prime reason for interfacial microannulus formation. Failure observed by the current study for wellbore pressure and temperature decrease (loading 4) for two different values of thermal expansion coefficient for formation rock is illustrated in Figure 7 below.

Results presented in Figure 8 demonstrate tensile (bond) stress-slip type of failure. Plot presented for three different scenarios show slip failure at peak normal stress of around 4.7 to 4.8 MPa. It is noticeable that till bond breakdown, all failure patterns are same. However, once debonded, microannulus widths for pressure and temperature decrease scenarios are larger than the pressure decrease scenario. All these aspects can be explained by the fact that due to temperature decrease, all material interfaces experience inward shrinkage which added to the total microannulus width. Further, once debonded, internal pressure decrease can only induce inward casing deformation which accounts for increase in microannulus width at casing-cement interface. However, higher value of thermal expansion coefficient for formation rock which corresponds to pressure and temperature decrease 2, does not affect much the microannulus formation. This is because, after debonding casing-cement interface is independent of the thermal behavior of formation rock (Figure 7).

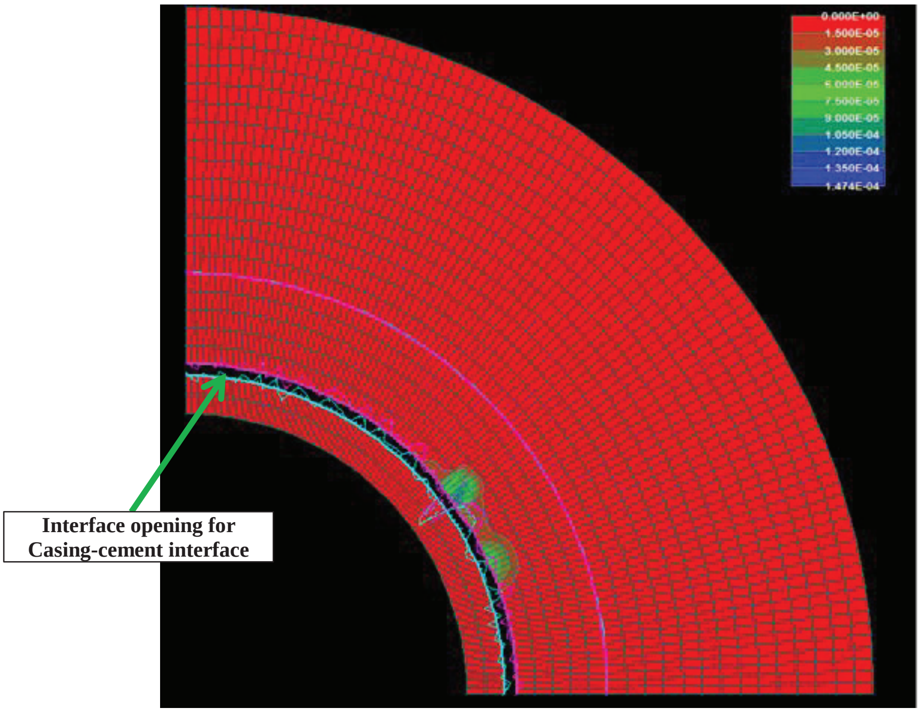

Figure 7. Direct tensile failure of casing-cement interface due to wellbore pressure and temperature decrease

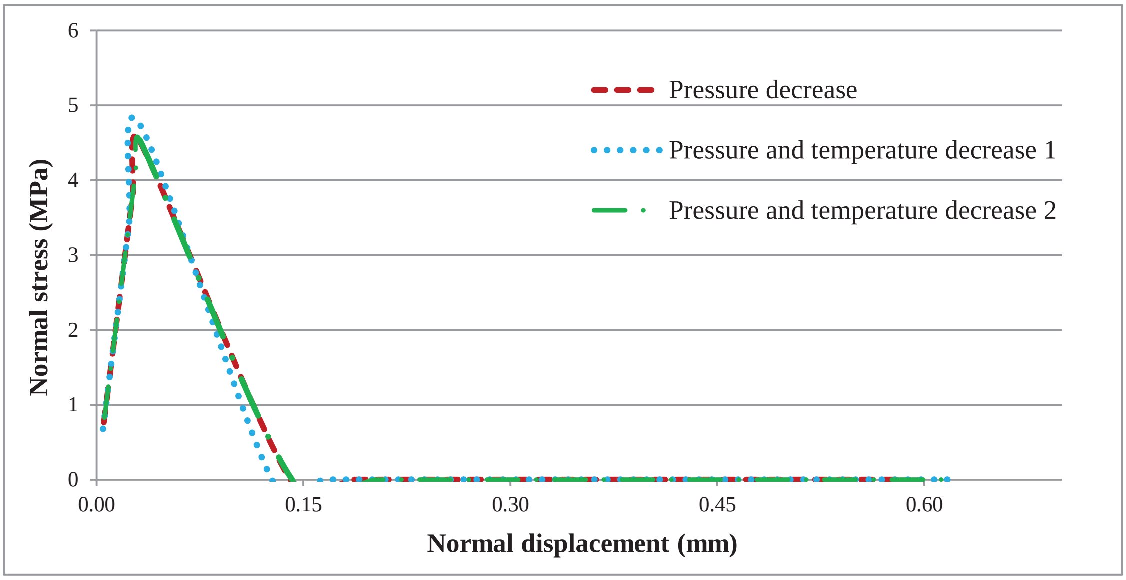

Figure 8. Micro-annular formation at casing-cement interface due to tensile radial stress

Figure 9 compares the Mohr-Coulomb failure surface for input material model for interfaces with shear stresses obtained from model output. It is observed that shear stresses developed during simulation are far below the maximum shear stresses represented by the input shear failure surface. Therefore it turns out that in case of wellbore pressure and temperature decrease, shear stresses developed over interfaces are insignificant and failure is dominated by the direct bond failure in the normal direction.

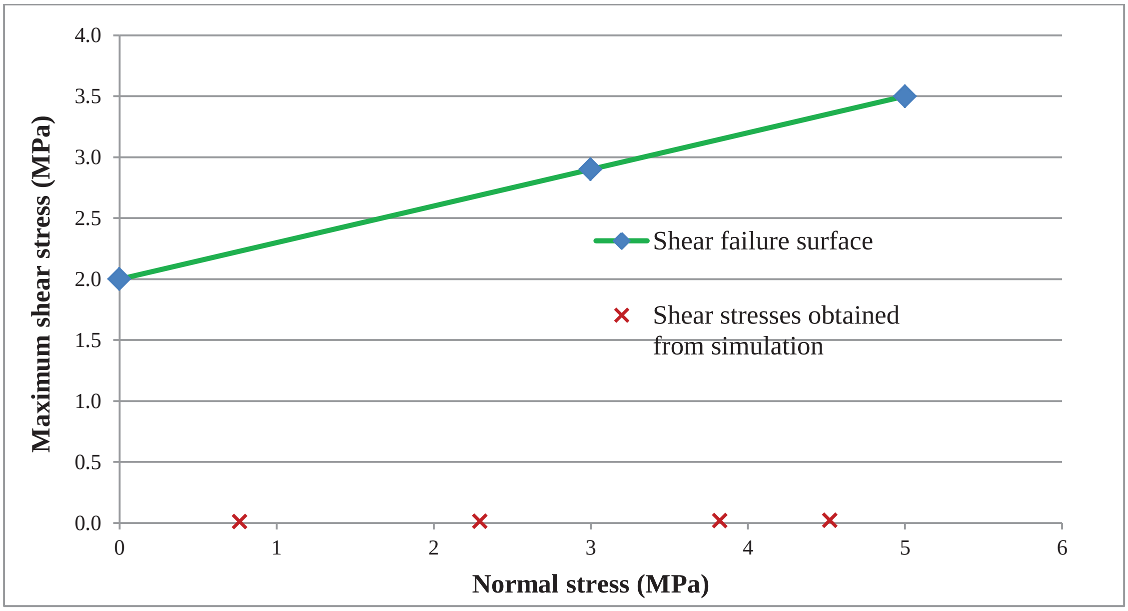

Figure 9. Shear failure surface and output shear stresses from simulation for casing-cement interface due to wellbore pressure and temperature decrease

From the above discussion, it is clear that defects along wellbore interfaces can occur even at low pressure and temperature loading. These defects can destroy well integrity when they are connected hydraulically. This is important because when a defect appears along interfaces, high pressure fluid flow can drive this up and establishes a full vertical channel. Therefore by reducing stress induced interfacial defects, associated risk of long-term CO_2 leakage could be minimized.

4. Conclusions

We conducted our simulation by using geopolymer cement properties as our model input. However, we observed many aspects related to wellbore interfacial debonding mechanism which may be applicable to conventional oil well cement as well. Conclusions noted from the study are presented below:

1. For a particular loading, initiation of tensile (radial) cracks around interface boundary indicates initiation of debonding and can be minimized by providing interfaces of adequate toughness.
2. For wellbore internal pressure and temperature increase, far end (cement-rock) contact fails first with discrete dislocation of interfaces; the location being at the point of intersection of radial crack with interface line. In this case, shear stresses developed along circumferential direction cause debonding. However, plastic shear stresses result in interface opening along normal direction, as well.
3. Higher thermal expansion of formation rock due to temperature increase help reducing growth of microannular width in case of wellbore pressure increase.
4. For wellbore internal pressure and temperature decrease, failure is induced by tensile stresses in the normal direction rather than interface shear stresses along tangential direction.
5. Material shrinks inward due to temperature decrease. This inward shrinkage gives rise to the overall micro-annulus width.

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